1. Introduction

Life cycle analysis is a well established environmental assessment method. The method is still evolving. Methodological problems have been identified in all stages (see e.g. [1,2,3,4] for a detailed discussion). For example costs are not considered in current LCA. However, costs are a key issue for policy making.

This paper focuses on one environmental problem, climate change caused by greenhouse gas (GHG) emissions. The paper will first discuss the consequences of current GHG policies for LCA of biomass products. The analysis will show that current LCA can result in misleading results for policy making. A dynamic life cycle model will be discussed for environmental assessment. Cost issues are endogenised in this approach. A case study for Western Europe shows the application of the model. Based on the case study, improvements are suggested for LCA.

The UNFCCC COP-3 meeting in Kyoto in December 1997 resulted in a protocol regarding GHG emission reduction in so-called Annex 1 countries. The Kyoto protocol covers six categories of GHGs: carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphurhexafluoride (SF₆). Apart from the emissions, biomass carbon sinks are taken into account (LUC Land Use Change) [5]. Different GHGs are aggregated on the basis of their global warming potential (GWP) for a time horizon of 100 years.

A significant fraction of Western European GHG emissions can be attributed to the life cycle of agricultural and forestry products (Table 1). However, its relevance is affected by the emission accounting practice. The column “biomass accounted” shows the GHG emissions that are considered in current emission statistics. The column “biomass real” shows the actual GHG emissions (that are really emitted). The figures show that especially an important fraction of the non-CO₂ GHG emissions is related to biomass. The total contribution of biomass of 450-550 Mt CO₂ equivalents represents 10-14% of total Western European GHG emissions. Table 1 shows the significant difference between “real” and “accounted” emissions (the difference is mainly carbon storage, see below). The three relevant GHG categories for agricultural products and forestry (CO₂, including LUC, CH₄ and N₂O) will be discussed below. PFCs, HFCs and SF₆ emissions have no direct link with biomass and will not be discussed any further.

CO₂

The bulk of CO₂ emissions is related to the combustion of fossil fuels. The CO₂-balance of biomass is generally considered to be neutral. CO₂ is absorbed from the air and stored in biomass carbon. This carbon from biomass is again converted into CO₂ if the biomass decomposes or if this biomass is incinerated (apart from the carbon that is transformed into CH₄ due to decomposition in landfill sites, see below).

The CO₂-neutrality is given if a stable system is considered (without changes of the carbon stock within the system). However, the biomass system is no stable system. 20% of the

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1 Paper prepared for the conference “LCA in Agriculture, Agro-Industry and Forestry”, 3-4 December 1998, Brussels
global CO₂ emissions are accounted for by deforestation, mainly in tropical countries. In Western Europe, the forest carbon stock is increasing. The forest area has been increasing since the last century, and is still further increasing. The average age of the forests is also increasing. Biomass carbon is stored in the increasing forest stock, in the increasing product stock, and in landfill sites (150-250 Mt CO₂, 75 Mt CO₂ and 25 Mt CO₂, respectively [7]). If this carbon storage is accounted for (in the column “biomass real”), the emission balance for agricultural and forestry products is significantly affected: the difference can be up to 300 Mt CO₂.

The negative emission for CO₂ in the column “biomass accounted” is completely accounted for by the energy recovery from biomass and waste biomass (e.g. in waste incinerators). Energy recovery from biomass is indirectly credited (it results in reduced fossil fuel consumption, hence it results in a GHG emission reduction). 75 Mt CO₂ emissions related to the energy use in the food processing industry are not accounted in Table 1 [6].

The Kyoto protocol is rather vague regarding the accounting of carbon storage. Interpretation suggests that carbon storage can only be accounted for forests planted after 1990. Biomass carbon storage in products and in disposal sites is probably not credited (but this is not explicitly stated). Net deforestation is fully accounted. Biomass trade cannot be credited to the producing countries. For example a biomass plantation in Brazil delivers wood to Europe. It is not allowed to account for the carbon storage in Brazil and to account the emission in the European country where the biomass is consumed.

CH₄
Ruminants (cows, sheep and goats) and manure storage are main agricultural emission sources (total approx. 200 Mt CO₂ eq.). The ratio of emissions is 4:1. For the vast majority of the world’s domestic ruminants consuming a wide range of diets under common production circumstances, CH₄ emissions fall near 6% of diet gross energy.

CH₄ emissions from landfill sites (approx. 200 Mt CO₂ eq.) are related to the decomposition of organic waste. The decomposition rate depends on the waste type. Cellulose and hemicellulose decompose, while the decomposition of lignin is more difficult. As a consequence of the composition, kitchen waste decomposes rapidly. Paper and wood require more time. The ultimate emission depends on the conditions in the landfill site and on the installation of landfill gas recovery systems.

N₂O
The N₂O emission includes the agricultural emissions related to fertiliser use and the industrial emissions in nitric acid (HNO₃) production. HNO₃ is an important intermediate in the production of ammonium nitrate, the most important nitrogen fertiliser. Part of this fertiliser is converted into N₂O by soil micro organisms. The use of all types of nitrogen fertilisers in the agricultural sector is a source of 30-50% of the total N₂O emission. This emission depends highly on the soil type. Agricultural N₂O emissions are related to the use of nitrogen (N) fertilisers (both synthetic fertilisers and manure). In some Western European countries, net degradation of organic soils adds to the N₂O emissions from fertiliser use.

The relation between fertiliser use and N₂O emissions is still poorly understood. Recently grazing animals on managed pastures and rangelands have been identified as significant contributors to the global N₂O budget. The average mean of the N excreted that is converted to N₂O is 2%. 1.25% of the fertiliser nitrogen input is converted into N₂O according to the IPCC emission accounting guidelines.

The application of fertiliser on grassland with high groundwater levels (such as parts of the Netherlands) results in emissions that are one order of magnitude higher than the emissions from the same fertiliser, applied on dry cropland. These differences are major sources of uncertainty.
Western European HNO₃ production amounted to 18.3 Mt in 1989. Production volumes have stabilised during the last decade. The process emission is approximately 3 ton CO₂ equivalents per ton HNO₃. The total Western European emission from this source is approximately 60 Mt CO₂ equivalents per year.

Table 1: Current emissions and the relevance of biomass, Western Europe (EU+EFTA), 1990/1995² [7,8]

<table>
<thead>
<tr>
<th>Category</th>
<th>GWP Total emission</th>
<th>Biomass</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[t CO₂ eq/t]</td>
<td>reference year</td>
<td>accounted</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[Mt CO₂ eq.]</td>
<td>[Mt CO₂ eq.]</td>
</tr>
<tr>
<td>CO₂</td>
<td>1</td>
<td>3388</td>
<td>-50 - -150</td>
</tr>
<tr>
<td>CH₄</td>
<td>21</td>
<td>520</td>
<td>300 - 400</td>
</tr>
<tr>
<td>N₂O</td>
<td>310</td>
<td>296</td>
<td>150 - 250</td>
</tr>
<tr>
<td>HFCs</td>
<td>140-11700</td>
<td>26</td>
<td>-</td>
</tr>
<tr>
<td>PFCs</td>
<td>6500-9200</td>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>SF₆</td>
<td>23900</td>
<td>19</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4260</td>
<td>400 - 600</td>
</tr>
</tbody>
</table>

The figures in Table 1 indicate the relevance of biomass flows and definitions for the GHG emission issue. Given the importance of GHG emission reduction for current environmental policies, GHG emissions will be a major issue in the LCA of many agricultural and forestry products. If LCA has to be used for policy making, the definition of GHG emissions should comply with the Kyoto definition of emissions (“biomass accounted”). Carbon storage is generally not considered in LCA. However, the storage dynamics may become relevant for policy making.

Model calculations indicate that reduction of non-CO₂ GHG emissions will be a key strategy for GHG emission reduction in Western Europe in the next decade (especially the emissions in HNO₃ production and the emissions from landfill sites [8,9]). As a consequence, the LCAs of agricultural products will be significantly affected. These effects must be accounted if LCA results are used for policy making. Few LCAs consider future changes in emissions yet.

**Emission valuation**

The United States, Japan and the European Union agreed in Kyoto to 6.7, and 8% emission reduction, respectively, in the period 2008-2012, compared to the emission in a reference year (1990/1995). The countries of the European Union agreed to a further distribution, ranging from -21% to +25%. Much further emission reductions in industrialised countries will be required beyond 2010, ranging from 75 to 90% of the 1990 emission levels. Developing countries, including the tropical countries (where most deforestation occurs) are no Annex I countries. They have no emission reduction goal. The range of emission reduction goals indicates that the selection of a policy goal for evaluation is a critical parameter for the evaluation of agricultural and forestry products.

What are the consequences of this analysis for biomass LCA? A number of issues have emerged:

- LCA GHG emission accounting should be tuned with the Kyoto protocol definitions
- how should carbon storage be treated in LCA
- policy goals for impact evaluation must be carefully selected (e.g. emission stabilisation will result in a very different valuation than a 75% emission reduction policy goal)
- changing emissions in time must be considered if LCA is used for decisions with a time horizon of more than 10 years

² The reference year is 1990 for CO₂, CH₄ and N₂O, 1995 for PFCs, HFCs and SF₆
³ Megatonnes CO₂ equivalents. 1 Mt = 10⁶ metric tonnes
⁴ Negative due to significant net carbon storage
2. Biomass for GHG emission reduction?

Biomass is a key resource that can help to reduce global GHG emissions and to increase the sustainability of our economy. Biomass can be used for materials, for energy, or in a sequence of both applications. It is not clear which strategy should be further developed in order to achieve the highest environmental and economic benefits.

Energy and materials biomass strategies for greenhouse gas emission mitigation can be split into:
- substitution of fossil fuels for energy and feedstocks
- substitution of CO₂-intensive materials by biomaterials
- substitution of non-renewable timber by renewable timber
- carbon storage in forests, products, and disposal sites
- increased recycling/reuse of biomaterials
- increased energy recovery from waste biomass

The availability of biomass in Western Europe is limited by the land availability and the biomass yields per square kilometre. This limits the potential of the biomass strategy for CO₂ emission reduction. This limitation must be considered in the analysis.

In order to identify cost-effective strategies for greenhouse gas emission reduction in the first half of the next century, an integrated techno-economic energy and materials system model has been developed for Western Europe. The analysis is based on the MARKAL (MARKet ALlocation) model. The model is currently used in a detailed analysis of biomass strategies within the BRED project, funded by the Environment and Climate Programme of the EU. The cost-effectiveness of the main biomass strategies has been analysed in a pilot study in order to identify the key issues for further research. Biomass strategies are compared to the other proposed strategies to reduce greenhouse gas emissions. Based on the model calculations, cost-effective biomass strategies will be identified. The results show whether energy or materials crops should be developed, which biomass applications should be developed, and how integrated bioenergy and biomaterial strategies increase the biomass competitiveness. The analysis will also show the pros and cons of dynamic optimisation models for life cycle analysis.

3. Modelling approach

The MARKAL linear programming model was developed 20 years ago within the IEA/ETSAP framework (International Energy Agency/Energy Technology Systems Analysis Programme). More than 50 institutes in 27 countries use nowadays MARKAL. A MARKAL model is a representation of (part of) the economy of a region. The economy is modelled as a system, represented by processes and physical and monetary flows between these processes. These processes represent all activities that are necessary to provide products and services. Many products and services can be generated through a number of alternative (sets of) processes. The model contains a database of several hundred processes, covering the whole life cycle for both energy and materials (Figure 1). The model calculates the least-cost system configuration. This system configuration is characterised by process activities and flows.
The database of processes and the constraints for individual processes and for the whole region are defined by the model user. Constraints are determined by the demand for products and services, the maximum introduction rate of new processes, the availability of resources, environmental policy goals for energy use and for emissions etcetera. Processes are characterised by their physical inputs and outputs of energy and material, by their costs, and by their environmental impacts. Environmental impacts are (through emission penalties) included in the process costs and the costs of energy and material flows between processes.

MARKAL is a dynamic model. The time span to be modelled is divided into nine periods of equal length, generally covering periods of decades. Within such a time horizon, technological change will be a major driving force for a changing systems configuration. Changing technology can be modelled through changing parameters in time for individual processes. Another option is the separate modelling of alternative processes. The model is used to calculate the least-cost system configuration for the whole time period, meeting exogenously defined product and service demands and meeting emission reduction targets. This optimisation is based on a so-called ‘perfect foresight’ approach, where all time periods are simultaneously optimised. Future constraints are taken into account in current investment decisions.

In order to show the comparability to LCA, Figure 2 details the materials system model structure. The model covers more than 25 energy carriers and 125 materials. More than 50 products represent the applications of these materials. 30 categories of waste materials are modelled. These materials are characterised by their physical characteristics and by their quality.
Different GHG emission penalties have been analysed. These penalties are shown in Figure 3. The base case is run without penalties. In the emission reduction cases, the penalties increase from zero in the year 2000 to their maximum level in 2020 and stabilise afterwards. These penalties represent different emission reduction goals. For example the 200 ECU/t CO₂ penalty approximately results in a factor 3 emission reduction in 2030, compared to the emissions in the base case.

An overview of the model structure is provided in [10]. Model input data and some analysis results can also be found on the Internet [11]. The model structure for biomass is illustrated in Figure 4 and Figure 5. Input data for biomass are discussed in [7].
4. **Comparison of MARKAL and LCA**

A comparison of the MARKAL approach and LCA is shown in Table 2. The main advantage of the MARKAL approach exists in the field of dynamic modelling. System dynamics due to the replacement rates of capital equipment and technological development are considered. The modelling approach includes technological progress in materials and product strategy.
analysis. Emission reduction policy goals, economic growth rates and key technological developments can be varied by the model user. The changing energy system configuration is endogenised in the model. The interactions and the trade-off between energy and materials policies can be analysed.

The dynamic approach allows the analysis of the relation between materials consumption and product demand in one year and waste release in the following years (see Figure 6).

Table 2: The integrated MARKAL energy and materials model compared to LCA

<table>
<thead>
<tr>
<th></th>
<th>MARKAL</th>
<th>LCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>System boundary</td>
<td>Region</td>
<td>Process chain ‘cradle to grave’</td>
</tr>
<tr>
<td>Calculation method</td>
<td>Cost minimisation (with endogenised environmental impacts)</td>
<td>Emission simulation</td>
</tr>
<tr>
<td>Time dimension</td>
<td>Included (storage, technological change, capital equipment stock, changing demand)</td>
<td>Not considered</td>
</tr>
<tr>
<td>Costs</td>
<td>Included</td>
<td>Optional</td>
</tr>
<tr>
<td>Time preferences (discount rates)</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Energy component</td>
<td>Detailed (e.g. variable CHP ratios, annual load curves etc.)</td>
<td>Aggregated (e.g. 1 electricity mix)</td>
</tr>
<tr>
<td>Impact valuation criteria</td>
<td>Marginal reduction costs, penalties</td>
<td>Current policy goals, environmental standards</td>
</tr>
<tr>
<td>Functional unit</td>
<td>Whole economy</td>
<td>Product, material etc.</td>
</tr>
<tr>
<td>Time horizon</td>
<td>Long term (&gt;10 years)</td>
<td>Short term (&lt;10 years)</td>
</tr>
<tr>
<td>Advantage</td>
<td>Dynamics considered, helicopterview</td>
<td>Simplicity, focus</td>
</tr>
<tr>
<td>Disadvantage</td>
<td>Complexity, large data requirements</td>
<td>May produce misleading results, allocation and valuation are problematic</td>
</tr>
</tbody>
</table>

Figure 6: Temporal system boundaries for the dynamic MARKAL approach compared to the static LCA and MFA approaches
Goal definition and inventory stage: system boundary definition and allocation
The allocation of environmental impacts of materials that can be produced through different production processes, or the allocation of the environmental impacts of different waste treatment processes that are applied for one material, is problematic in LCA. A closed system approach prevents allocation problems. Western Europe, the system that is studied with MARKAL, represents to a large extent a closed system. Another type of emission allocation problems arises for processes with multiple inputs and outputs, e.g. the emissions during combustion of mixed waste. Ideally, burdens should be allocated between outputs or inputs according to the marginal variation of each burden in response to the marginal variation of each output or input, respectively. For a linear system, allocation by marginal variation in a Linear Programming approach, like MARKAL, does allocate all burdens completely [12].

Inventory stage: changing emissions in time
Technological change is generally not considered in LCA studies. However technological change is a major cause for changing environmental performance of products and processes over a period of decades. Interactions between improvement strategies in different product life cycles can be analysed with MARKAL. It is important to consider such interactions, because they can influence the environmental balance of products and they can decrease the environmental benefits of individual improvement options.

Impact assessment
Valuation of environmental impacts is in LCA generally based on current standards and current policy goals. Emissions are in MARKAL valued according to the marginal emission reduction costs, given a certain policy goal, or according to the emission penalty that is set by the model user. The policy goals can differ per period. It is for example foreseeable that the environmental policies regarding GHG emission reduction will be more strict in the next decades. An emission valuation, based on current short-term policy goals, is in such cases inadequate. Because LCA does not consider the time axis, all emissions are valued according to the same standards. In MARKAL, costs are discounted. Because environmental impacts are endogenised in the costs, they are also discounted. This effect can be very substantial for long-life products. Because LCA does not consider the time axis, discounting is not applied.

Limitations
The confinement to GHG emissions avoids some major analysis problems. The regional distribution of emissions (in order to account for local threshold levels) does not matter in the case of GHG emissions. The analysis is limited to emission levels, actual consequences of climate change are not considered.

Scientific points of critique that have been encountered are:
• material flows between regions within the system are not considered
• markets for globally traded materials, e.g. aluminium, are not adequately represented
• materials do only to a limited extent compete on the basis of prices
• the real market is not an ideal market
• the model contains only one electricity grid, while dedicated power plants may be used for dedicated industries (such as hydropower plants for aluminium smelters)
• the model does not consider subsidies and taxes, which determine the decision making by actors in the economy, e.g. in agriculture, for transportation fuels, and in the residential heating market.

The model should be considered as a step in the search for improved rational decision making. The model poses a framework for further analysis on a more detailed level.

5. Case study
MARKAL results show significant reductions of the emissions in materials production, in case emission penalties are applied. Figure 7 shows the CO₂ intensity of steel, cement and PVC for the base case and for the emission penalty cases.
The differences between the base case and the reduction case are very significant. The figures show that 60-90% emission reduction is achieved. These changes can be attributed to a cost-effective mix of emission reduction options in materials production. The changes affect the comparison of the environmental impacts of biomass products and other products.

All biomass input into the production process for these materials (including by-products that are ultimately used for energy purposes) is allocated to the category biomaterials. For example all wood input into pulp production is allocated to the category materials (including the fraction that ends up in black liquor). Bioenergy encompasses all biomass which is directly used for energy purposes (such as solid biomass fuels for electricity production and heating, and biomass used for production of liquid transportation fuels).

The use of biomass for energy and for materials is detailed in Figure 8. The figure shows that biomaterial applications dominate in the base case and in the emission penalty cases up to a penalty of 100 ECU/t CO₂. Only in the case with a 200 ECU/t penalty, the energy applications dominate.
Sensitivity analysis for land availability

The availability of surplus agricultural land in Western Europe in the next three decades is highly uncertain. It depends in many interacting parameters. In modelling terms, the scenarios are translated into a land availability of 2 million hectares and 22 million hectares, respectively. The 22 million hectare scenario has been used in the reference scenario model calculations, the 2 million hectare represents the sensitivity analysis.

Figure 9: Biomass use for energy, depending on land availability, increasing GHG penalties, 2030

Figure 9 shows the impact of land availability on the use of biomass for energy production. The impact is significant at penalty levels of more than 20 ECU/t CO₂. The gap between both scenarios increases to around 300 Mt biomass at penalty levels of 200 ECU/t upward. The main part of the difference between the 2 Mha and 22 Mha case can be attributed to the production of ethanol from lignocellulose crops. For biomaterials, the impact is less significant.

In GHG emission terms, the difference between both scenarios increases to approximately 100 MT CO₂ equivalents at higher emission penalties (from 100 ECU/t CO₂ upward). This difference represents 5-10% of the total GHG emissions at these penalty levels or approximately 3% of the GHG emissions in the base case.

6. Conclusions

Agricultural and forestry products can contribute significantly to GHG emission reduction. As a consequence, GHG emissions deserve special attention in the LCA of these products. The Kyoto protocol poses certain problems regarding the biomass carbon accounting that should be considered.

Changing GHG emissions in time must be considered if the LCA results are used for policy making. Non-CO₂ GHG emissions will be significantly reduced in the next decade. CO₂ emissions will be significantly reduced beyond that period.

GHG emission reduction is characterised by a time horizon of several decades. Within such a time horizon, a number of issues must be considered for proper environmental assessment:
- the changing reference energy/materials system must be considered (changing energy production, changing materials production and changing waste handling)
• changing long term policy goals must be considered. GHG emissions constitute a typical example of an environmental problem that will gain increasing importance in future environmental policies. GHG emission impacts will dominate the future environmental balance of many agricultural and forestry products.

MARKAL results show a rapid decline in the CO₂ emissions related to materials production in a case with CO₂ emission reduction penalties. Average emissions per unit of material (for all types of materials) that are generally reduced by 60-90%. This type of changes must be considered in the evaluation of the long term environmental impacts of agricultural and forestry products, compared to other products. GHG emission reduction penalties will increase the use of both bioenergy and biomaterials.

The analysis of long term environmental policies requires broad system boundaries, often extending beyond the life cycle of individual products. A large number of combinations of improvement options must be considered. Systems optimisation models such as MARKAL can be used for the quick analysis of the impact of such complex interactions on a product life cycle. It is recommended to develop a simpler method for product design, based on a mix of LCA and optimisation models. For example MARKAL results regarding future emissions per tonne material can be used as an input for life cycle analysis. Another option is to add LCA data to MARKAL for dynamic life cycle analysis.

7. References


[11] http:\\www.ecn.nl\unit_bs\etsap\markal\matter\